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Planetary Magnetospheres

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INTRODUCTION

Emanating non-uniformly from the Sun's corona at 300-700 km s^{-1} is a hot, tenuous, magnetized, and mainly hydrogenous plasma, spreading radially throughout interplanetary space and known as the solar wind (SW). Whenever this flow encounters a planetary body with a sufficiently intense magnetic field, an asymmetrical cavity is formed, impeding direct entry of the solar wind into it. Such cavities are called magnetospheres, a term coined by Gold [1959], reflecting the fact that the principal forces acting on charged particles within the cavities are of magnetic or electric origin, in contrast to atmospheres which are bound by gravity.

Four magnetospheres have been explored so far in our solar system. All of them have been found to possess long magnetic tails which, like cometary type II tails, point away from the sun in the solar wind flow. The Earth [Langel et al., 1980] has a magnetic moment $M_E = 7.906\ 10^{25}$ gauss cm^3 (= $7.906\ 10^{15}$ tesla m^3) and its field blocks the SW from approaching closer than about 10 R_E (Earth radii; 1 R_E = 6371.2 km) on the sunward side. The resulting magnetosphere has been extensively studied by spacecraft since 1958 [Williams, 1976; Akasofu, 1977, 1980a; Nishida, 1978; Kennel et al., 1979; Olson, 1979] and is described in more detail below.

Jupiter has a very large magnetic moment, about $1.53\ 10^{30}$ G cm^3 $\approx$ - 20,000 M_E (minus denotes an opposite polarity), and four spacecraft have only recently explored its huge and dense magnetosphere: Pioneers 10/11 in 1973-4 [Science, 1974, 1975; J. Geophys. Res., 1974; Gehrels, 1976; Kennel and

Coroniti, 1977; Smith & Gulkis, 1979] and Voyagers 1/2 in 1979 [Science, 1979a, b; Nature, 1979; J. Geophys. Res., 1981b]. Saturn is less strongly magnetized [Science, 1980, 1981, 1982; J. Geophys. Res., 1980; Nature, 1981; Dessler, 1982], with a magnetic moment $\sim 4.06\ 10^{28}$ G cm^3 or about $\sim 500\ M_E$, and its magnetosphere, though extensive, is rather rarefied. The magnetospheres of both giant planets are affected by planetary rotation much more than that of Earth, and absorption of trapped plasma and energetic particles by satellites and rings also modifies their structure. In addition, Jupiter's magnetosphere is strongly affected by the large satellite Io, which appears to be heated by tidal action [Peale et al., 1979] and from which active volcanos emit sulfur and oxygen into space. Io is the source of much of the heavy ion plasma filling Jupiter's magnetosphere and it affects some of the planet's diverse radio emissions [Carr et al., 1982].

Mercury has a relatively small magnetic moment, estimated from the Mariner 10 encounters at $5\ 10^{22}$ G m^3 $\sim +0.63\ 10^{-3}\ M_E$ [Ness, 1979a, b] . Observations suggest that Mercury's magnetosphere is too small to maintain a trapped plasma population around the planet but that impulsive acceleration of charged particles may occur on the distended nightside of the cavity.

The possibility has also been raised that the four Galilean satellites of Jupiter and the Saturnian satellite Titan may be magnetized like Mercury [Neubauer, 1978; Kivelson et al., 1979], but no compelling evidence for any such fields exists so far.

Other bodies examined so far in the solar system lack extensive magnetization. At Venus [Breus, 1979; Russell, 1980; Gringauz, 1981] the SW interacts directly with the ionosphere, producing a bow shock (since the SW velocity usually exceeds the Alfvén velocity) and a long wake. The moon intercepts and absorbs the SW directly and thus produces no shock, only a wake [Ness, 1979b], and though it may be weakly magnetized in patches, no appreciable plasma effects are associated with this magnetization. Mars, like Venus, has an atmosphere and therefore produces a shock, as well as a wake; Russian spacecraft observations have led to some claims for a weak internal field, near the limit of detection [Ness, 1979b; Russell, 1980; Gringauz, 1981]. Finally, satellites such as Io and Titan, embedded in a rotating

magnetosphere, produce wakes that may be subsonic or transonic, sub-Alfvénic or trans-Alfvénic. Comets also may have large scale electromagnetic interactions with the solar wind. All such cavities are not regarded as "proper" magnetospheres here and are not considered.

A limited review can cover no more than an outline of the extensive observations and theories concerned with planetary magnetospheres. This overview is keyed to the interests of astronomers and astrophysicists and its references will be mainly texts, reviews, and special publications, through which more detailed information can be traced.

Planetary magnetospheres have a special position in astrophysics, because they constitute the only natural environment in which many astrophysically important processes can be studied in situ. The bow shocks ahead of magnetospheres, for instance, have provided extensive information about collision-free shocks. Particle acceleration is another example [Haerendel, 1981]: in the Earth's magnetosphere, a number of distinct acceleration processes have been studied, while acceleration mechanisms in solar flares, supernovae, and more distant sources remain largely a matter of conjecture. A large number of plasma wave modes have been observed in the Earth's magnetosphere, and there may exist an even richer variety near Jupiter, judging by observed radio spectra. Finally such processes as particle trapping and diffusion, magnetic merging (or "reconnection"), and magnetic-field-aligned voltage drops ("$E_{\parallel}$") have first been studied directly in the Earth's magnetosphere, and though many unsolved questions about them remain, their astrophysical significance is probably considerable.

MAGNETOSPHERIC MORPHOLOGY

Overall Structure

The solar wind at 1 AU [Neugebauer, 1976] has a typical density of n = 5-10 cm^{-3}, a velocity v = 300-700 km s^{-1} and a magnetic field of about 5 nT (1 nT = 10^{-5} gauss). A collision-free shock forms about 14 R_E upstream of the Earth [Fairfield, 1971], followed about 3 R_E further earthward by the boundary of the magnetosphere, the magnetopause (Figure 1). While the detached bow

shock diverges at a wide angle, the magnetopause on the nightside tends to a nearly cylindrical shape and attains a radius of about 25 R_E near the moon's orbit ($\sim$ 60 R_E). Only a few observations of the nightside magnetosphere at greater distances exist, and they suggest that its structure becomes variable and irregular.

THE BOW SHOCK The properties of the bow shock depend strongly on Mach number, density, and other SW parameters [Greenstadt & Fredricks, 1979; Kennel, 1981; J. Geophys. Res. 1981a], but most of all on the angle between B and the shock normal. When that angle is small ("quasi-parallel shock") "preshock" precursors exist and the shock profile is wide and ragged, when the angle is near 90^o, the transition is compressed to a few hundred km [Greenstadt et al., 1975]. The region behind the shock is known as the magnetosheath, with $n_e \sim$ 10-15 cm^{-3}, v $\sim$ 250-300 km s^{-1} as typical values; however, the flow rapidly regains its supersonic/Alfvénic parameters as it passes abeam of the Earth [Fairfield, 1976].

Observations upstream of the bow shock by ISEE-3, orbiting near the Earth-Sun Lagrangian point 235 R_E sunward of Earth, have revealed [Scholer et al., 1980] backscattered protons of about 100 keV, which seem to have undergone acceleration at the shock. A lower energy backscattered population has also been detected; theories of the processes involved are being developed and may be relevant to shock acceleration in general.

THE MAGNETOPAUSE The magnetopause is also rather variable [Fairfield, 1979]. Early observers interpreted it as a tangential discontinuity, maintained by a pressure balance between the SW on the outside and the Earth's magnetic field on the inside. Such a balance often (though not always) occurs at the boundary near the point where it crosses the Earth-Sun line, and it has provided a rough guide for the magnetopause location in magnetospheres other than the Earth's. In general, however, the properties of the boundary are more complex [Sonnerup, 1976], and a small magnetic field component perpendicular to it may exist, as predicted by the open model of the magnetosphere, (described below). In addition, plasma contained inside the magnetosphere can contribute appreciably to the pressure, so much so that cases exist in which the crossing of the magnetopause is far more evident in the plasma population

than it is in the magnetic field.

The magnetopause is typically 500-1000 km thick [Russell & Elphic, 1978] and is generally in motion, due in part to variations in the SW parameters, though on the flanks there seem to exist surface waves excited by the Kelvin-Helmholtz instability [Lepping & Burlaga, 1979]. These motions are somewhat similar to ripples on a flag in a breeze. A "boundary layer" is often observed just inside the magnetopause, especially on the nightside [Rosenbauer et al., 1975]; its thickness is 0.5-4 R_E and its plasma flow parallels that of the SW but at a fraction ($\sim$ 1/4) of the density and speed.

The Inner Magnetosphere

EARTH: ADIABATIC MOTION. The interior of the magnetosphere may be divided into two main regions, the inner magnetosphere and the magnetic tail. Charged particle motions in the inner magnetosphere are characterized by three independent periodicities, each conserving an adiabatic invariant of the form $\oint p\,dq$ [Northrop & Teller, 1960; Anderson, 1966; Rossi & Olbert, 1970]. The fastest periodicity is that of gyration around field lines, conserving the magnetic moment $\mu = p_\perp^2/B$, where $p_\perp$ is the component of the particle momentum $\underset{\sim}{p}$ orthogonal to $\underset{\sim}{B}$. While this gyration (for typical magnetospheric energies) is confined to a rather small radius, charged particles are less restricted in their motion along magnetic field lines. However, the constancy of μ prevents a charged particle from proceeding past its mirror points at which $B = B_m = p_\perp^2/\mu$, so that such particles are reflected and bounce back and forth along their guiding field lines between points at which $B = B_m$ (Figure 2). This "bounce" constitutes a second periodicity ($\sim$ 0.1 s) with a "longitudinal (adiabatic) invariant" $J = \oint p_\parallel\, ds$, where s is the distance along the guiding field line.

RING CURRENT A third periodicity [$\sim$ 30 min; table 6.1 of Rossi & Olbert, 1970] involves a slow drift of particles from one guiding field line to the next, gradually moving them around Earth, westward for ions and eastward for electrons. This is a result of the spatial variation of the magnetic field and the finite gyroradius of the particles. Thus a net electric current arises, (the ring current) consisting (for Earth) mainly of particles in the 10-100

keV range. It is the intensification of this ring current that causes worldwide "<u>magnetic storms</u>," in which B at the surface of the Earth drops within hours by up to 1-2%, gradually recovering within a day or two.

It was long believed that the ionic component of the ring current consisted almost exclusively of solar wind protons, and it came as a great surprise when, beginning in 1971, an appreciable content of O^+ ions was observed [<u>Johnson</u>, 1979; <u>Balsiger et al.</u>, 1980]. Such ions are the dominant positive species in the Earth's ionosphere but are absent in the solar wind (where any O is more highly ionized). Thus their presence gave an early clue to the acceleration of particles by voltage drops along magnetic field lines (see below).

The drift motion is particularly simple for equatorial particles: if W is their energy, $W/B = m\mu/2$ is conserved, so that if W is also constant (as happens when the electric field $\underset{\sim}{E}$ vanishes or is weak enough to be ignored) such particles stay with a constant field intensity B. Equatorial particles grazing the noonside magnetopause at 10 R_E, where B is strengthened by compression, will pass through the midnight meridian at a distance of only about 8 R_E, which is typical of the distance of transition to the geomagnetic tail.

COROTATION AND CONVECTION The above drifts are all related to the inhomogeneity of $\underset{\sim}{B}$ and are roughly proportional to the particle energy W. In addition, any electric field $\underset{\sim}{E}$ contributes a drift velocity $\underset{\sim}{u} = \underset{\sim}{E} \times \underset{\sim}{B}/B^2$, independent of W or the electrical charge. Thus $\underset{\sim}{E}$ (or more precisely, its component orthogonal to $\underset{\sim}{B}$) may be viewed as the agency by which a bulk motion is imparted to magnetospheric plasma, and two classes of such motions are of particular significance [<u>Stern</u>, 1977]. First, there exists <u>corotation</u>, imparted to the ionosphere ($n_e \sim 10^6$ cm^{-3} at $\sim$ 200 km altitude; e.g. <u>Ratcliffe</u>, 1972) by collisions with the neutral atmosphere and transmitted from there to the rest of the magnetosphere by a suitable $\underset{\sim}{E}$.

Secondly, there seems to exist (perhaps intermittently; details below) a dawn-to-dusk electric field across the magnetosphere and its tail, with a total voltage drop of 20-100 kV, creating a sunward <u>convection</u> of plasma from

the tail to the dayside [Axford, 1969]. This field may cause particle energization in the Earth's magnetosphere and results from the magnetic field of the solar wind sweeping past Earth, as described below.

PLASMAPAUSE The boundary between the regions dominated by either convection or corotation seems to lie along field lines crossing the equator at 4-5 R_E ("field lines with L=4 to 5") and has been identified with the plasmapause, a steep increase in n_e from $\sim$ 1 cm^{-3} to 10-100 cm^{-3} [Chappell, 1971; Carpenter & Park, 1973; Rycroft & Lemaire, 1975]. The region inside the plasmapause is known as the plasmasphere and seems to be filled with fairly dense plasma of ionospheric origin. In contrast, polar field lines outside the plasmapause may undergo a steady plasma loss [Lemaire & Scherer, 1973], and ionospheric depletions due to the arrival of auroral particles also seem to occur.

JUPITER The magnetosphere of Jupiter (Gehrels, 1976; Kennel & Coroniti, 1977; Goertz & Thomsen, 1979) is dominated by a powerful and radially extensive ring current that distorts its more distant part into a disklike configuration (Goertz, 1979; Connerney et al., 1981); its dominant particle energies are not accurately known but may resemble those of the Earth's ring current (Krimigis et al., 1979a, b). The dominant source of plasma does not appear to be the planetary ionosphere but rather gases ejected from the volcanoes of the satellite Io. These gases become ionized and fill a torus-shaped cloud (r = 5 to 7 R_J) in which n_e can reach 2000 cm^{-3} (Warwick et al., 1979). Corotation seems to dominate other plasma motions up to the boundary, though some slippage has been noted and a nonrotating tail has been observed (Ness et al., 1979b; Behannon et al., 1981b).

Because the Jovian dipole is tilted by 9.6° to the rotation axis, the symmetry surface of the field ("equatorial surface") is also tilted, though at larger distances it may bend to become more parallel to the rotation equator (i.e. the Jovian "centrifugal equator" flaps back and forth in the course of each rotation). Thanks to this tilt, a spacecraft encountering the planet observes a 10-hour modulation in magnetic and plasma properties, persisting to the boundary and even into the magnetosheath (Lepping et al., 1981).

The trapped particle flux increases towards the planet and its radial profile (Fillius, 1976) contains distinct local minima due to absorption by major satellites and also by the thin Jovian ring at 1.8 R_J, whose existence was predicted on such grounds before it was observed by Voyager 1. The overall flux intensity is quite high and the total dosage to Pioneer 10, which came within a radial distance of 2.84 R_J, was 1-3 10^5 rads, sufficient to degrade some instruments (Fillius & McIlwain, 1974).

IO The innermost Galilean satellite of Jupiter, Io, at an average radial distance of 5.95 R_J, plays a special role in the Jovian magnetosphere. Pioneer 10 observations (Kliore et al., 1974) revealed that it had a nonsymmetrical ionosphere, and this suggested that a closed conducting circuit could exist, containing Jovian field lines and completed by the ionospheres of Jupiter and Io (Figure 3).

Because of the relative motion between Io and the rest of this circuit (motion due mainly to corotation of the magnetosphere, not to Io's orbital speed), a large net emf (600 kV) develops, with a substantial current flow. Since the circuit is long and narrow, the current is shaped like a double filament; further considerations (Neubauer, 1980; Southwood et al., 1980) suggest deformation of the current, because Io's relative speed is an appreciable fraction of the local Alfvén velocity. Voyager 1 was targeted toward the Io flux tube, and the magnetic signature of its current was detected (Ness et al., 1979a; Acuña et al., 1981), indicating a flow of 2-3 10^6 amp.

The Voyager 1 encounter also unexpectedly revealed eight volcanic plumes on Io (Strom et al., 1979). These plumes are probably due to the tidal heating of the interior, which was predicted before the encounter (Peale et al., 1979). The volcanoes emit mainly sulfur compounds such as SO_2 and seem to be the source of the "plasma torus" circling Jupiter, enclosing Io and about 2 R_J wide. This cloud contains mostly S and O, as well as some Na that had been detected spectroscopically from the Earth before the encounter; from the composition of the more distant Jovian magnetosphere (Sullivan & Bagenal, 1979) it seems that Io may also supply most of the plasma at greater distances. Of course, the volcanic activity of Io is expected to be variable and could have been unusually high during the Voyager encounters.

The correlation between Io's position and Jovian decametric radio emission has been known for many years (Carr & Gulkis, 1969) and is described elsewhere.

SATURN The magnetosphere of Saturn is somewhat similar to that of Jupiter except that the field is weaker, the trapped particle fluxes are lower and no source of plasma comparable to Io seems to exist. One anomalous feature is that the magnetic dipole axis of Saturn is inclined only $\sim 1^{\circ}$ to the rotation axis. The ring current causes less distortion than that of Jupiter, and the mean energy of its particles seems to be lower (Krimigis et al., 1981). An interesting feature is the sharp and almost total cutoff of all trapped particle fluxes at the outer edge of Saturn's "A ring" (around 2.3 R_S). Variations in the radial intensity profile have been observed and some of these have been ascribed to absorption by satellites, though additional sources of variability also seem to exist.

NEUTRON ALBEDO BELTS In addition to the "soft" particles of the ring current, the Earth's radiation belt also contains an "inner radiation belt" of relatively energetic protons (30-150 MeV), extending in the equatorial plane between distances of 1.2 and 2.5 R_E ("field lines with L = 1.2 to 2.5"). Such protons seem to be decay products of secondary (albedo) neutrons ejected from the Earth's atmosphere by cosmic ray particles (Walt & Farley, 1976).

The source feeding this inner belt is rather weak, since the cosmic ray

flux is low and so too is the probability that the decay of an albedo neutron occurs close enough to Earth for the resulting proton to be captured. Thus, the very existence of an "albedo belt" indicates that its particles have relatively long lifetimes. Indeed, an artificial radiation belt cr ted by a nuclear explosion in the same region, relatively close to the Earth's equator (J. Geophys. Res., 1963) lasted for years (Beall et al., 1967), while similarly injected particles on more distant field lines (J. Geophys. Res., 1959) decayed within days. Saturn apparently also has an albedo belt (Cooper and Simpson, 1980). Most of the neutrons, in that case, appear to originate from collisions of cosmic ray particles and their charged secondaries with the planet's ring system.

The Tail

COORDINATES In what follows, solar magnetospheric coordinates are useful. In that system, the x axis points sunward, the x-z plane contains the geomagnetic dipole axis (with $z > 0$ at the north pole), and the y axis completes the cartesian set. The origin is at the Earth's center, so that x is positive on the day side and negative on the night side.

Local time. Local time (LT) of a given point on Earth, at any instant, is usually taken as a function of the azimuthal angle ϕ between it and the noon meridian: if ϕ is (0°, 90°, 180°, 270°), LT is (12, 18, 24 or 0, 6) hours, also known as (noon, dusk, midnight, dawn). In magnetospheric applications, LT usually means magnetic local time, with longitude measured around the magnetic axis and $\phi = 0$ on the half-plane containing the magnetic axis and the Sun.

TAIL LOBES In the inner magnetosphere the field configuration is that of a deformed dipole, but around $x = -8\ R_E$ a rapid transition begins and past $x = -15\ R_E$ the field lines are almost aligned with the x axis. Beyond this distance the magnetopause becomes almost cylindrical, its radius increasing slowly up to around 25 R_E (Howe & Binsack, 1972), while the interior may be divided into 3 parts, northern and southern tail lobes, separated by the tail's plasma sheet (Figure 1).

In the northern tail lobe, field lines are essentially headed earthward ($B_x>0$) as is appropriate for field lines entering the northern hemisphere, while in the southern lobe the direction is reversed ($B_x<0$). Typical values of the field intensity B (for $-x = 20$-35 R_E) are 10-20 nT, with B_x accounting for most of this. The plasma density n can be extremely low, of the order of 0.01 cm^{-3}, and the ratio β between plasma energy density and magnetic energy density is much smaller than 1.

PLASMA SHEET (PS) Separating the lobes in the middle of the tail is a thick layer of hot plasma, the plasma sheet (Hill, 1974; Schindler & Birn, 1978); it is approximately centered on a plane $z = z_o$, where the constant z_o depends on the angle between the z axis and the dipole axis and may reach ± 4 R_E when that angle is largest (Fairfield, 1980; Stern, 1976, Fig. 1). The undisturbed plasma sheet is about 5 R_E thick (it is thicker near the flanks, in agreement with theory—see Schindler, 1979), has typical density $n \sim 0.5$ cm^{-3}, and a typical plasma population peaked around 2-5 keV for ions and 0.5-1 keV for electrons. In contrast with the lobes, $\beta \sim 1$.

In general, $B_z>0$ in the plasma sheet (typical values are 1-2 nT) suggesting that field lines there, though stretched out, are anchored on Earth. The surface separating opposite signs of B_x is commonly called the neutral sheet (NS); actually $\underset{\sim}{B}$ rarely vanishes there (B_z remains), but it is sufficiently weak to render the motion of most protons nonadiabatic (Williams, 1981). On occasion $B_z<0$ is observed, which may reflect either an undulation of the neutral sheet or the creation of closed "loops", bounded by X-type neutral points (Figure 6). An analysis of observations (Caan et al., 1979) suggests that both situations may occur.

The rapid reversal of B_x at the neutral sheet indicates that an electric current flows across the plasma sheet from dawn to dusk, amounting to about 10^5 amp. per R_E length; this current is probably completed by the boundary current of the magnetopause, where a boundary layer (Rosenbauer et al., 1975) is often seen. The tail structure described here persists at least up to the orbit of the moon (60-70 R_E); beyond that distance few observations exist (Villante, 1977).

OTHER PLANETS Studies of tail structures in other magnetospheres suffer from lack of data. The Pioneer 10 and 11 trajectories near Jupiter were confined to the sector of LT = 5-12 h; Voyagers 1 and 2 made their exits around a LT of 4 and 3 h respectively (Stone & Lane, 1979, Figure 2), and their observations (especially those of Voyager 2) confirmed the existence of a tail resembling Earth's (Ness et al., 1979b; Behannon et al., 1981b). Observations of intervals when the SW flow ceased, about 3 AU downstream from Jupiter (Scarf et al., 1981), suggest that this tail is extremely long. It should be noted that the intense Jovian ring current flattens the outer parts of its entire corotating magnetosphere to a profile rather similar to that of the Earth's tail, including a thin "neutral sheet" (Goertz, 1979): thus the transition to the tail is less noticeable than it is near Earth.

In past encounters with Saturn's magnetosphere, Pioneer 11 did not pass the nightside tail while Voyager 1, which made its exit around LT = 3 h, did find some signs of a tail (Behannon et al., 1981a). Observations of particle anisotropies during that time (Krimigis et al., 1981) suggested that trapped particle orbits extended all the way to the magnetopause, raising the possibility of an "inner" magnetosphere extending much further tailward than expected. Mercury's tiny magnetosphere (Ness, 1979a,b; Whang, 1979) appears to have a well-developed tail, in which sporadic particle acceleration may occur (Siscoe et al., 1975).

The Polar Caps

IONOSPHERIC CONDUCTIVITY As noted, particle motions in the magnetosphere are guided by magnetic field lines, and motions along such lines are less restricted than motions orthogonal to them. It is thus no surprise that in space plasmas the local electrical conductivity parallel to $\underset{\sim}{B}$, denoted by σ_0, is very large. By contrast, the Pedersen and Hall conductivities (σ_1 and σ_2) directed along $\underset{\sim}{E}$ and $\underset{\sim}{B}\times\underset{\sim}{E}$, are only significant in the ionosphere, where they peak (for Earth) at 100-150 km and rapidly become negligible higher up (Boström, 1964). It should be noted, however, that most electric currents in the magnetosphere (e.g. the ring current) are unrelated to conductivity and do not arise in response to any $\underset{\sim}{E}$.

This near-infinite value of $\sigma_{\parallel}$ suggests that any electric field component $E_{\parallel}$ parallel to B will tend to be shorted out; if $\underset{\sim}{E} = -\nabla\Phi$, the potential Φ along field lines is then constant, so that each line acts like a highly conducting wire. From such reasoning one expects the polar caps around the magnetic poles to be linked electrically to distant regions of the magnetosphere and perhaps to the solar wind as well.

POLAR AURORA The most visible expression of this linkage is the polar aurora, a luminosity produced at altitudes of 90-130 km by the arrival of electrons with energies of 0.5-20 keV (Hultqvist, 1975; Eather, 1975, 1980; Whalen & McDiarmid, 1976; Akasofu, 1977; Meng, 1978; Swift, 1979); its light is mainly due to the 5577A (green) and 6300A (red) lines of oxygen, and precipitation of protons and He ions has also been observed. The aurora is not concentrated near the magnetic poles, but occurs mainly in the auroral oval, a near-circular band several degrees wide, typically centered at magnetic latitude 77^{o} at noon and 68^{o} at midnight (Eather, 1973). This suggests that most auroral particles do not arrive directly from the Sun (as once was believed) but instead are energized inside the magnetosphere; in fact, recent evidence indicates that much of the acceleration occurs below 10,000 km by processes that suggest $E_{\parallel} \neq 0$ (Evans, 1975, 1976; Stern, 1979b; Swift, 1981).

Auroras are classified by various properties (Davis, 1978; Swift, 1979): for instance, temporal behavior distinguishes quiet, pulsating (Johnstone, 1978), surge, and breakup auroras, the last two of these associated with substorms (see below). In another classification, discrete auroras form well-defined bright arcs and are probably associated with acceleration by $E_{\parallel}$, while the diffuse type, located further equatorward, may arise when ring current particles are scattered by plasma waves into trajectories that hit the atmosphere. Additional types are stable auroral red (SAR) arcs, occurring at lower latitudes and apparently not related to other types (Rees & Roble, 1975), and dayside cleft auroras (Shepherd, 1979; Mende et al., 1980), containing solar wind particles that have entered the "cleft" or "cusp" (Figure 1) between field lines that close on the dayside and those swept tailward.

FIELD-ALIGNED (BIRKELAND) CURRENTS A second feature of the auroral oval are current sheets flowing along magnetic field lines into the ionosphere and out of it, amounting typically to 1-3 10^6 Amp (Iijima and Potemra, 1976; Potemra, 1979). There exist two systems of such currents (Figure 4), the poleward one ("region 1"), entering the ionosphere on the dawnside and leaving it at dusk, and the equatorward one ("region 2") having opposite flow directions. The typical current density is 1 $\mu A/m^2$, and the upflowing sheets seem to be associated with discrete auroras.

Region 2 currents are about half as intense as those of region 1, peak on the nightside, and increase sharply during magnetic disturbances; it is widely held that they are caused by plasma convected earthward from the tail (Schield et al., 1969) and that they are linked to region 1 currents by means of ionospheric Pedersen currents. The ionospheric Hall current associated with the flow between the sheets then takes the form of two dense filaments, flowing nightward along the boundary between the sheets (Figure 4) and converging around LT = 22 h., at the so-called Harang discontinuity. These currents, known as the westward and eastward auroral electrojets, have been observed for a long time by the magnetic effects ("bays") they produce at ground level (Rostoker, 1972b; Bostrom, 1968); the remainder of the flow produces a relatively small magnetic disturbance near the ground (Fukushima, 1976) and has only been confirmed after satellite magnetometers mapped the sheets. The "middle layer" of currents near the Harang discontinuity (Figure 4) may represent a current filament carrying away the positive charge entering there by the confluence of the electrojets.

ELECTRIC FIELD The currents of region 1 are probably driven by the polar electric field (Cauffman & Gurnett, 1972; Heppner, 1977; Stern, 1977), directed roughly from dawn to dusk in the interior of the polar cap and having a typical voltage drop between 20 and 120 kV. Equatorward of a "reversal boundary" aligned with region 1, $\underset{\sim}{E}$ reverses to become roughly dusk-to-dawn (Figure 4); this reversed $\underset{\sim}{E}$ may be viewed as the fringing pattern of the main polar field. The ionospheric currents driven by the reversal field are consistent with the Pedersen currents noted earlier (and with the Hall currents comprising the electrojets). When the field is mapped along field lines to the nightside equatorial magnetosphere, it produces drifts there that

are consistent with the earthward convection of plasma (Figure 1).

The polar electric field provides a major energy input from the solar wind to the magnetosphere and probably arises because field lines of region 1 extend into the solar wind (see below), creating a dynamo mechanism that qualitatively resembles the current loop between Io and Jupiter (Figure 3). The part of the region 1 current which does not continue to region 2 (about half of the total) connects across the polar cap (and along the auroral oval). The outflow and inflow of region 1 close in the solar wind, in analogy with the Io-Jupiter current; this current appears to be most intense on the dayside and weaker on the nightside, where it may pass through the plasma sheet before reaching its solar wind sources.

MAGNETOSPHERIC PROCESSES

The Open Magnetosphere

The polar electric field and the associated streaming of plasma suggest that the interaction of the solar wind (SW) with the Earth's magnetosphere follows one of two basic patterns (Stern, 1977; Johnson, 1978). In the closed magnetosphere (Figure 5a), a closed boundary surface tangential to field lines completely encloses the magnetosphere and separates it from the SW; external plasma can then only enter through the cusps, or when "plasma blobs" breach the boundary (Lemaire, 1979). However, the SW can also interact with the interior by means of viscous forces, which may drag magnetospheric plasma adjoining the boundary in the nightward direction. The electric field associated with such motion maps into the polar cap along the dawn-to-dusk direction; the plasma dragged tailward ultimately returns to the dayside along paths closer to the x axis. This accounts for the sunward convection and its associated (reversed) $\mathbf{E}$.

In the open magnetosphere, by contrast, open field lines from the polar caps extend into interplanetary space (Figure 5b). Now, the MHD relation $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ esssentially governs the flow, and it implies that two particles that share a field line at any time must do so at all times, unless at some instant

a neutral point (NP), where $\underline{B} = 0$, comes between them. Since "open" field lines contain both interplanetary and ionospheric particles (which cannot very well be permanent fieldline partners), the particles strung along such lines must pass through a neutral point -- a process known as magnetic merging or reconnection -- when they first become linked to the magnetosphere and again, further downstream, when they become detached. Magnetic merging is thus essential to the existence of the open magnetosphere. A return convection in the region of closed field lines, from the tail to the dayside, is also predicted by this model.

Observations appear to favor the open model, mainly because of the strong correlation of magnetospheric phenomena with the interplanetary magnetic field (IMF), in particular with the component B_z of the IMF. The magnetic polarity of Earth is such that field lines enter its northern polar cap and emerge from its southern one, so that when $B_z<0$ ("southward IMF") the attachment of merged lines is "easy" (Figure 5b), while if $B_z>0$ each field line half must bend around before becoming attached to the appropriate polar cap. Therefore $B_z<0$ is more conducive to strong SW-magnetosphere coupling, in accord with observations: polar caps are larger when $B_z<0$ (Meng, 1980), more energy appears to be transmitted to the magnetosphere (Akasofu, 1980b), substorms are more frequent, and other effects also exist (Burch, 1974; Nishida, 1975). In addition, the B_y component of the IMF produces a variety of asymmetries in the polar caps (Burch, 1979; Meng, 1980; Cowley, 1981); other evidence favoring the "open" model includes the arrival pattern of solar flare particles (Paulikas, 1974) and the existence of rarefied tail lobes.

Magnetic merging has been extensively studied theoretically (see Vasyliunas, 1975; Sonnerup, 1979; Stern, 1979b) and has often been postulated in astrophysics as a means for rapid release of magnetic energy and particle acceleration, especially in solar flares (Svestka, 1976). It is therefore remarkable that in dayside merging, where the evidence for merging is strongest, the process appears to be quiescent (Haerendel et al., 1978) with a few possible exceptions (Paschmann et al., 1979). A "mirror image" process of reconnection on the nightside (Figure 5b) has not been observed; it may occur too far downstream and/or be disordered (turbulent), or else it may be intermittent and occur mainly during substorms (below) when merging of a violent energy-releasing nature apparently occurs in the near-Earth tail (around $-x$ = 10–15 R_E).

Little is known about the topology of other planetary magnetospheres, though Jupiter's magnetosphere is surmised to be open, since tail "signatures" have been observed in it. Unlike the case of Earth, where the "lifetime" of an open field line between merging and reconnection is only $\sim$ 1 h (limiting its distortion by planetary rotation), open Jovian lines (with the same scaling) are expected to last many full planetary rotations and may therefore be severely twisted (Schulz, 1976).

Acceleration

Mechanisms of particle acceleration play a central role in high-energy astrophysics and in solar flares, and several such mechanisms are observed in the magnetosphere.

For example, earthward convection of near-equatorial particles increases their energy W approximately in proportion to the ambient magnetic intensity B, since $W_{\perp}/B$ is conserved; for particles making wide excursions from the equatorial plane, the quantity approximately conserved is Ws^2, where s is the length of the guiding field line. In both cases the acceleration is what E.N. Parker has termed "undemocratic," favoring those particles that already are energized to some extent since the energy gain is proportional to the initial

value of W. Particles accelerated in this fashion may of course be convected out again and lose energy by the same process. Observations exist of energetic Jovian electrons, and at times of energetic terrestrial particles as well, in interplanetary space (Pyle, 1979), but such particles may have been accelerated in other ways.

A different acceleration mechanism involves neutral points (NP) or neutral lines (NL), classified as X-type or O-type according to the field line structure in their vicinity. A popular view regards merging near such points or lines as a "magnetic field annihilation" process, in which plasma flows into a NL (or NP) with an appreciable B, but leaves with $B \sim 0$ and with most of its magnetic energy $B^2/2\mu_0$ transmuted into particle energy. In such a process each particle stands to gain the most energy if $\beta \ll 1$. Thus the tail lobes are best suited for this mode, which may be the source of relatively high-energy particles sometimes produced by substorms (Krimigis & Sarris, 1980). Sheet configurations (Priest, 1976) or O-type lines (Stern, 1979a) allow the outflow of plasma only along a NL and thus could be better suited for this type of acceleration than X-type lines, where most of the plasma skirts the region of weak B.

Perhaps the least expected mechanism has been acceleration by an electric component $E_\parallel$ parallel to $\underset{\sim}{B}$, first deduced from rocket observations of auroral electrons (Evans, 1975, 1976) and confirmed by other evidence, such as accelerated O^+ ions rising from the ionosphere (Johnson, 1979). The total parallel voltage drop could extend to the typical auroral energy cutoff of 10-15 kV, though a few kV seems to be more common. The existence of $E_\parallel$ may be reconciled with the near-infinite value of σ_0 in one of two ways. Either (Fredricks, 1975; Papadopoulos, 1977) σ_0 is diminished by collective interactions of the plasma ("anomalous resistivity"), triggered when the parallel current density $j_\parallel$ exceeds a rather modest threshold; or else (Stern, 1981) $E_\parallel$ must be treated by noting the way in which it perturbs the entire motion between mirror points, rather than locally (using σ_0). The latter approach suggests that part of the parallel potential drop occurs in abrupt voltage discontinuities ("double layers"); even before, theoretical studies of such discontinuities were conducted (Block, 1978), ascribing them to a variety of causes. The observation of two distinct populations of accelerated O^+

ions, "beams" and "conics" (Gorney et al., 1981), may be a hint that perhaps both mechanisms do occur.

Additional acceleration modes include those that take place at bow shocks and the mild energization ($\sim$ 700 eV) of heavy ions from Io by electromagnetic processes that cause them to corotate with Jupiter. Particles diffusing radially from weak to strong B also may be energized in much the same way as they are by convection (though other particles, diffusing in the opposite direction, lose energy by the same process).

Substorms

The level of "activity" in the magnetosphere, as expressed by convection, particle acceleration, auroral displays, and electrojet intensity, varies widely. At times when $B_z<0$ in the solar wind, such activity peaks at irregular intervals ($\sim$3 h) in great convulsions known as magnetopsheric substorms ("sub-" because the main magnetic disturbance is local to the auroral zone, in contrast to magnetic storms which are worldwide). Substorms (Rostoker, 1972a; Akasofu, 1977, 1980a; Nishida, 1978; McPherron, 1979) last about half an hour, though their main energy release may be quite rapid ($\sim$ 1 min.), suggesting parallels with solar flares (Schindler, 1976). At the onset of a substorm, the aurora near midnight expands and brightens ("expansion phase"); in the tail, the plasma sheet is squeezed by the lobes and becomes very narrow ("thinning"), and in other parts of the sheet fast flows ($\sim$ 1000 km s^{-1}) are observed, directed either earthward and tailward. Closer to Earth [e.g. in synchronous orbit (6.6 R_E)] and near midnight, sudden flux increases mark the arrival of freshly accelerated particles (DeForest & McIlwain, 1971). In addition, the auroral electrojets intensify, and the resulting groundlevel magnetic disturbance can be used for deriving an "AE index" (Rostoker, 1972b), gauging the storminess level.

Though many studies of substorms exist, all interpretations are still controversial. One such interpretation starts from the observation that substorms are few and weak when $B_z>0$, but may start within an hour or less of a "southward turning" to $B_z<0$. During such periods the polar cusp has been observed to migrate equatorward (Burch, 1974), reflecting "erosion" of

magnetic flux on the dayside (Coroniti & Kennel, 1973), i.e. the shifting to the nightside (by an increased rate of merging, due to a more favorable B_z) of magnetic flux that previously had closed on the dayside. To accommodate the additional flux, the angle ψ by which the tail flares out then increases (Figure 6), making the tail a wider obstacle to the solar wind. The added pressure is transmitted to the plasma sheet, where it causes thinning. An O-type bubble ("plasmoid"; Hones, 1976) may form (Figure 6) and be expelled nightward, while the inner part of the plasma sheet is squeezed earthward in a burst of enhanced convection. When this finally subsides, particles convected earthward may discover themselves in trapped orbits, unable to drift out again (Roederer & Hones, 1974).

Why additional substorms occur after B_z has turned negative is less clear; perhaps the rate of merging and of flux return to the dayside vary quasi-periodically, so that ψ also fluctuates. The argument has also been made that substorms are inevitable because there exists no stable way of smoothly closing the tail on the nightside. Similar episodes of abrupt acceleration also seem to occur on the nightside of Mercury (Siscoe et al., 1975).

Some unresolved controversies remain: (a) Does a substorm release energy stored beforehand in a stressed magnetic field, or does it merely signify (Akasofu, 1980b) a higher rate of energy transfer from the solar wind? (b) Are particles accelerated locally along an "injection boundary" near the inner edge of the plasma sheet, as some analyses suggest (DeForest & McIlwain, 1971)? (c) Is the increase in the ring current that marks a magnetic storm always caused by a sequence of substorms preceding it? (d) Does there exist a "build-up" or "growth" phase preceding the substorm, and if so, what is its relation to certain changes observed in particle populations in the inner magnetosphere prior to a substorm onset? (e) Is part of the cross-tail current diverted through the ionosphere during a substorm? All of these may well require simultaneous observations by a network of satellites on the night side before they can be elucidated.

Waves

Magnetospheric plasmas are capable of sustaining a bewildering variety of waves (Shawhan, 1979a,b). Some (not all) are modified electromagnetic waves (Stix, 1962) and often have twin modes, somewhat like waves in anisotropic crystals but with anisotropy determined by $\underline{B}$. The earliest observations of such waves in the Earth's magnetosphere involved whistlers (Al'pert, 1980), emissions of low frequency ($\sim$ 3 kHz) generated by lightning and guided by geomagnetic field lines and "ducts" of enhanced ionization from one hemisphere to the other. Whistlers provided the first clue for the existence of the plasmapause and have recently been artifically injected for studies of wave-particle interactions (Helliwell, 1974; Helliwell & Katsufrakis, 1974).

Most magnetospheric waves, however, seem to originate locally in unstable plasmas with a non-Maxwellian and/or anisotropic distribution function F. Some anisotropy is always present, for at any point in the magnetosphere there always exists a bundle of trajectories with F = 0 intersecting the atmosphere ("loss cone"). Observations and theory both suggest (Kennel & Petschek, 1966; Schulz, 1975; Gendrin, 1975; Lyons, 1979) that when trapped particles exceed a certain density threshold, waves arise and scatter them, causing a steady precipitation through the loss cone until the density drops and the waves cease.

Other modes include low-frequency "hydromagnetic" waves (Lanzerotti & Southwood, 1979), some of them perhaps generated by flapping of the magnetopause (Lepping & Burlaga, 1979); electrostatic wave bands observed near (n + 1/2) times the local electron gyration frequency (n = 1, 2 .. ,7); low frequency "auroral hiss," and many others. The most intense mode is the auroral kilometric radiation (AKR), apparently emanating at radial distances above 2 R_E from beams of auroral electrons, with "kilometric" wavelengths and typical frequencies between 150 and 200 kHz (too low to pass the ionosphere and reach the ground). The mean intensity of the AKR is $\sim 10^7$ w (peaks at 10^9 w). The AKR escapes in the right-hand extraordinary mode and is correlated with magnetic activity; different explanations for this radiation have been proposed, but the ultimate solution may depend on in situ observations in its

region of origin.

JUPITER Jupiter is a much stronger radio source than Earth, and bursts of "decametric emissions" from its magnetosphere (DAM, now known to extend over 1-40 MHz) were discovered as early as 1955 (Carr & Gulkis, 1969). Since 1964 DAM has been known to be modulated by the position of Io, and observations by Voyager 1 and 2 (Warwick et al., 1979; Carr et al., 1982) have shown that its spectral variations exhibit a complex pattern that remains to be explained. Emissions in the decimetric wavelength range have also been extensively observed (de Pater, 1981) and are a result of synchrotron radiation from energetic electrons; such radiation has also been observed from an artificial radiation belt around Earth (J. Geophys. Res. 1963). In addition, the Voyagers observed a variety of emissions at lower frequencies.

SATURN Saturn is a weaker radio source than Jupiter. Its broadband "kilometric" radiation (10-1100 kHz) somewhat resembles Jupiter's DAM, but the emission structures are less sharply defined in frequency and time (Boischot et al., 1981). The radiation is emitted asymmetrically (even though Saturn's magnetic field comes remarkably close to being axially symmetric around the rotation axis) and from this a rather precise value of the rotation period (10 h 39 min 24±7 s) was derived (Desch & Kaiser, 1981). Saturn also emits brief bursts (duration ~ 0.1 s, frequency up to 40 MHz), which might originate in electrostatic discharges in the ring system (Evans et al., 1981).

SUMMARY

Planetary magnetospheres (the Earth's in particular) provide a natural laboratory for studying the behavior of space plasmas. Their intricate behavior is being gradually resolved into definite patterns, and inklings of understanding are beginning to emerge. By combining in situ observations and theory, much has been learned about particle acceleration, plasma waves, large-scale plasma flows, collisionless shocks, $E_{\parallel}$, magnetic merging, the role of planetary rotation and of moons such as Io, and about many other processes. Such knowledge will not only provide a better understanding of planetary environments but will also become a benchmark for the plasma physics of the rest of the Universe, where in situ observations are not feasible.

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Abbreviations used: JGR -- J. Geophys. Res.
RGSP -- Rev. Geophys. Space Sci.

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Captions to Figures

Figure 1 - Three-dimensional schematic view of the Earth's magnetosphere.

Figure 2 - Adiabatic motion of a charged particle in the Earth's magnetosphere (drawing not to scale: actually the spiral shrinks greatly near the mirror points).

Figure 3 - The electric current linking Io with the northern hemisphere of Jupiter (drawing not to scale); a mirror-image current leading to the southern hemisphere is shown by a dotted line. The magnetic polarity of Jupiter and the relative velocity of Io are also indicated, as are the rotation axis and the magnetic equator.

Figure 4 - Electric currents and fields in the northern polar cap of Earth: curves are typical electric equipotentials, while shaded regions are areas where field-aligned currents (on the average) meet the ionosphere. Light shading signifies upward currents, dark shading downward ones. (All coordinates are geomagnetic, centered at the magnetic pole.)

Figure 5 - (a) Schematic view of the closed magnetosphere (not to scale);
(b) Schematic view of the open magnetosphere (not to scale).

Figure 6 - One view of the substorm process.

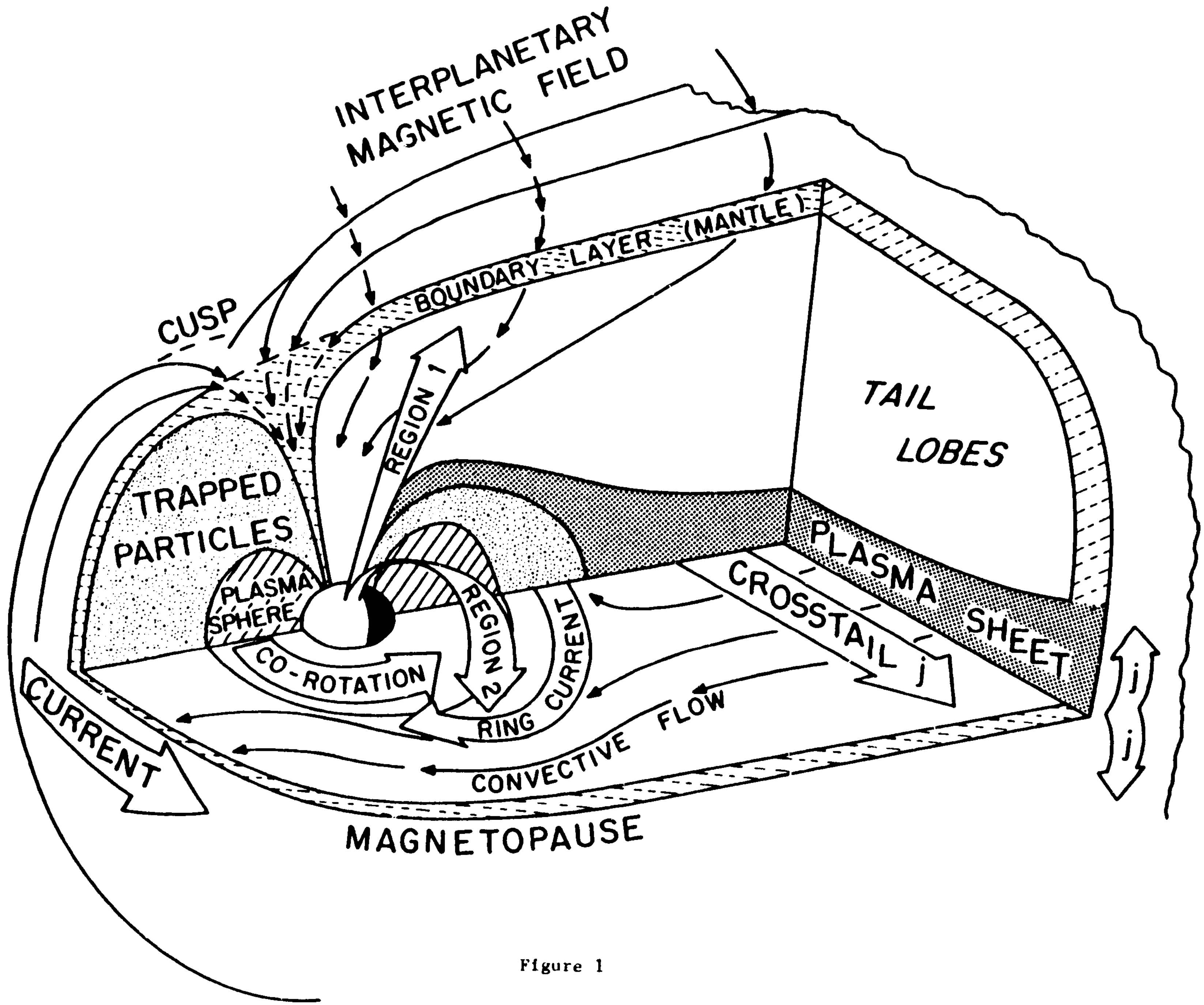
INTERPLANETARY
MAGNETIC FIELD
CUSP
BOUNDARY LAYER (MANTLE)
TAIL
LOBES
REGION 1
TRAPPED
PARTICLES
PLASMA
SPHERE
REGION 2
CO-ROTATION
RING CURRENT
PLASMA SHEET
CROSSTAIL j
j
j
CONVECTIVE FLOW
CURRENT
MAGNETOPAUSE

Figure 1

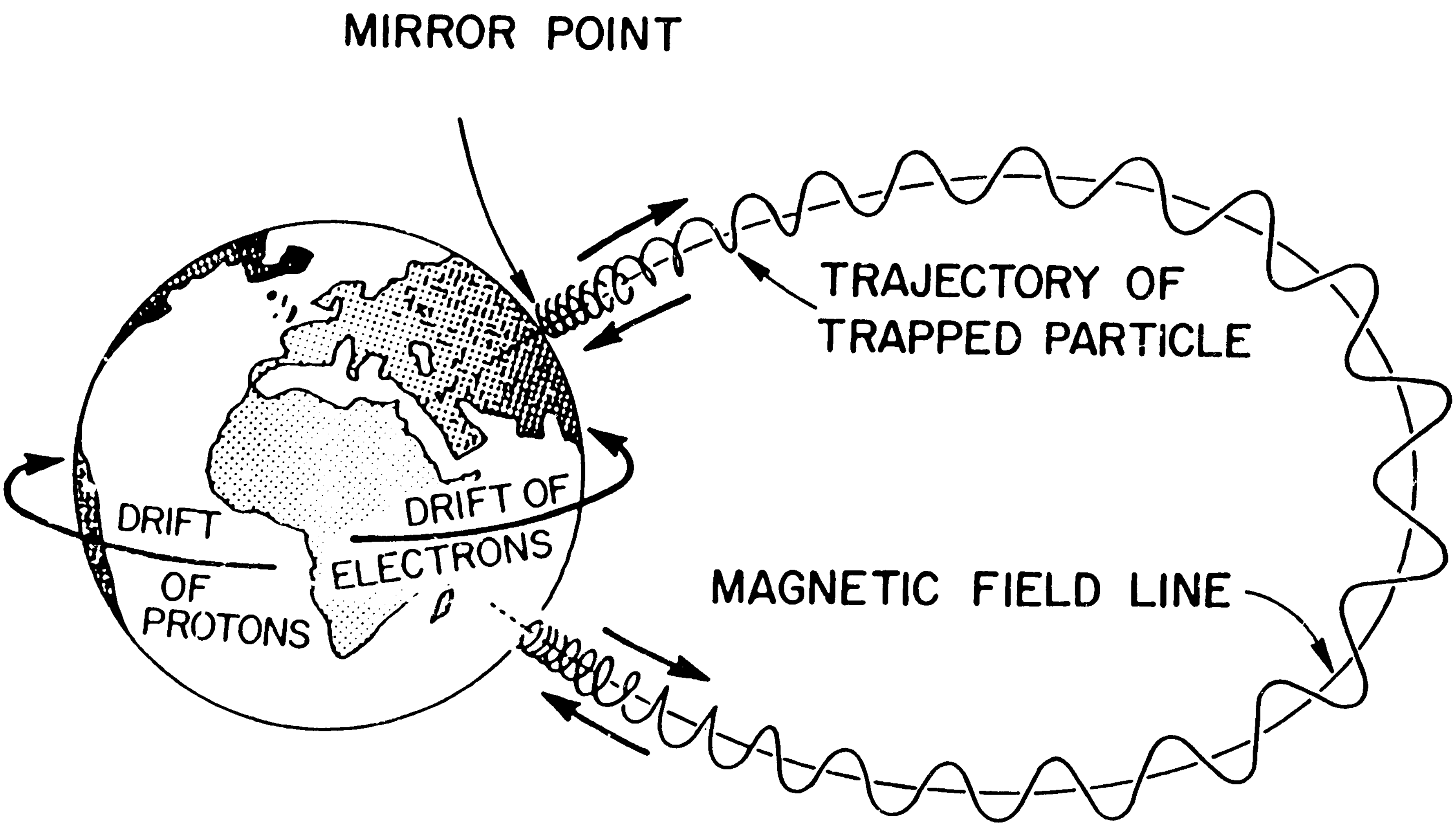
MIRROR POINT
TRAJECTORY OF
TRAPPED PARTICLE
DRIFT OF
ELECTRONS
DRIFT
OF
PROTONS
MAGNETIC FIELD LINE

Figure 2

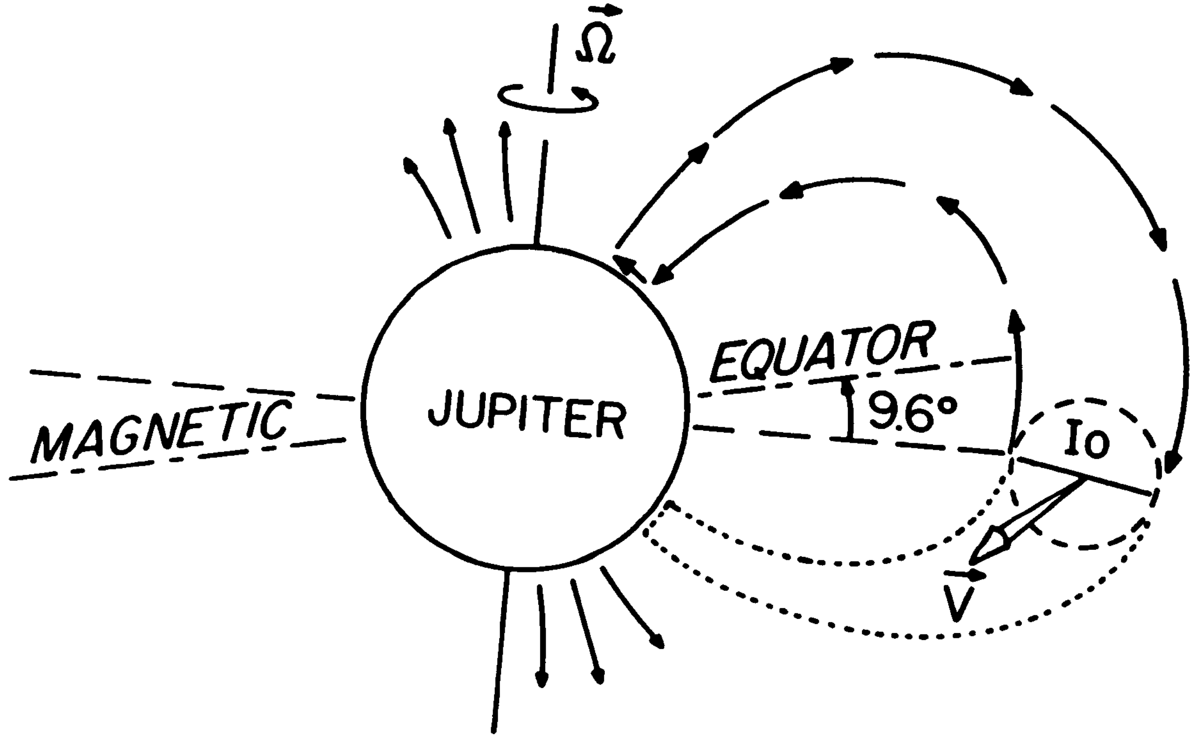

Figure 3

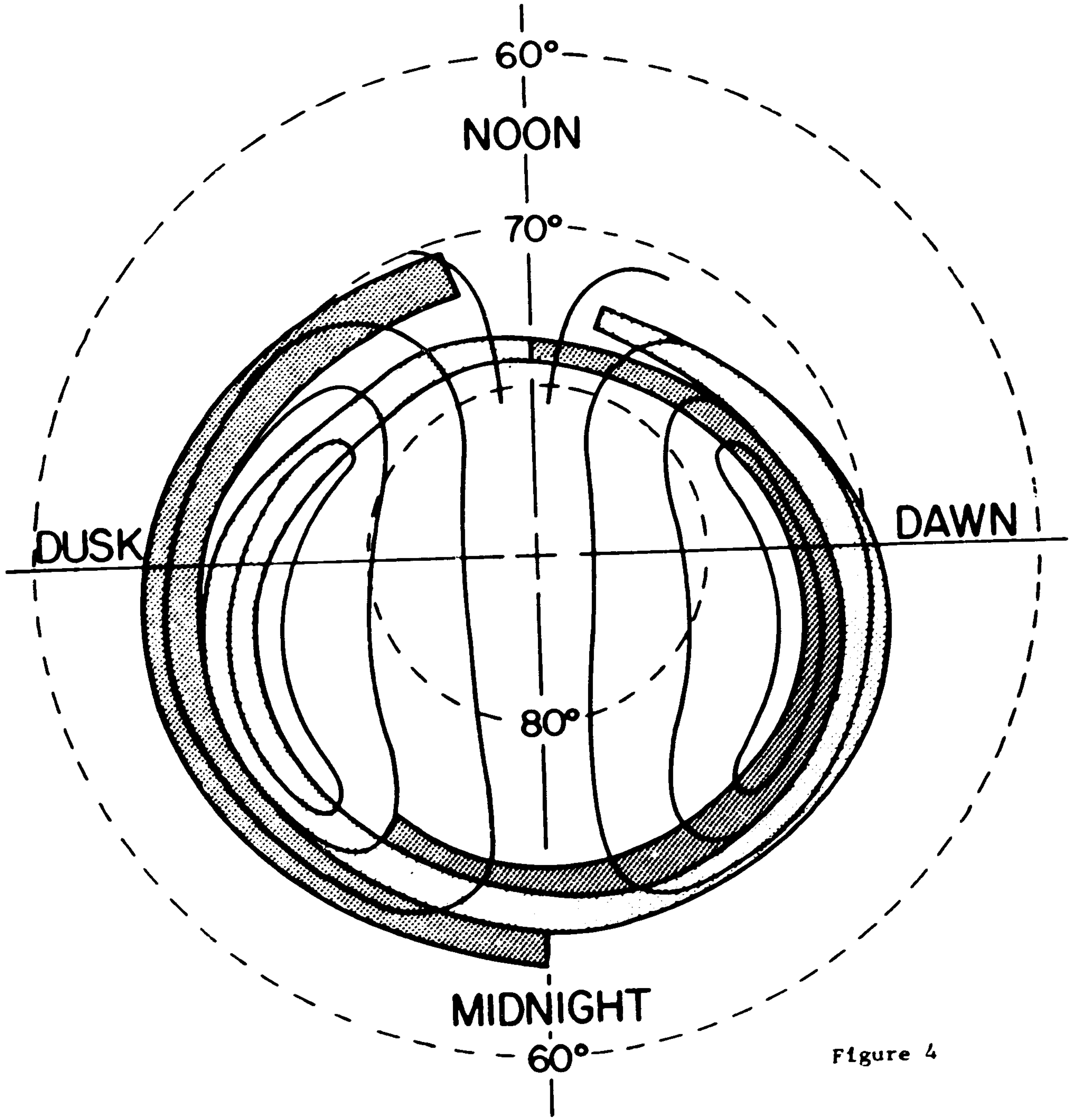

Figure 4

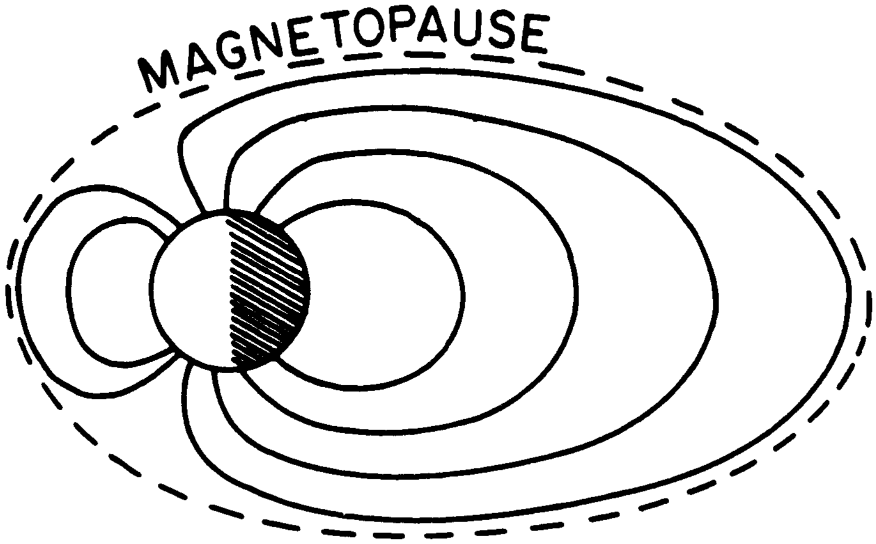

Figure 5a

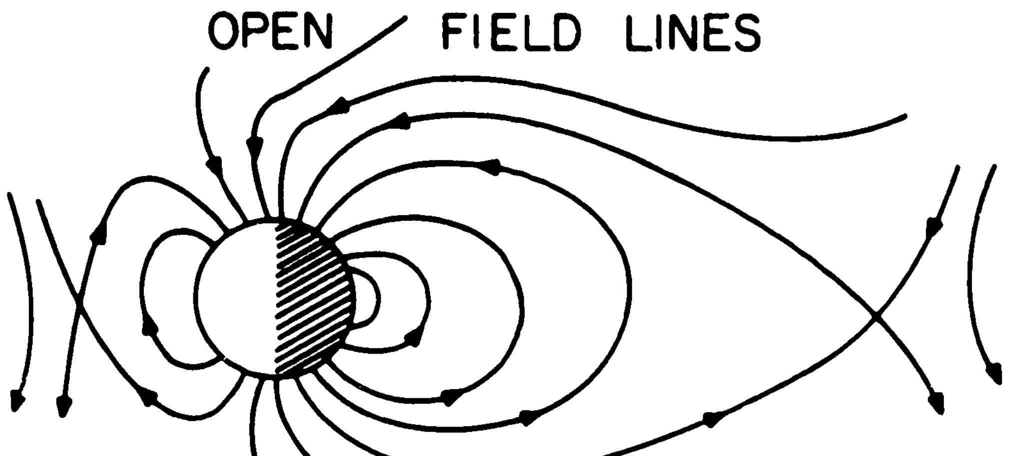

Figure 5b

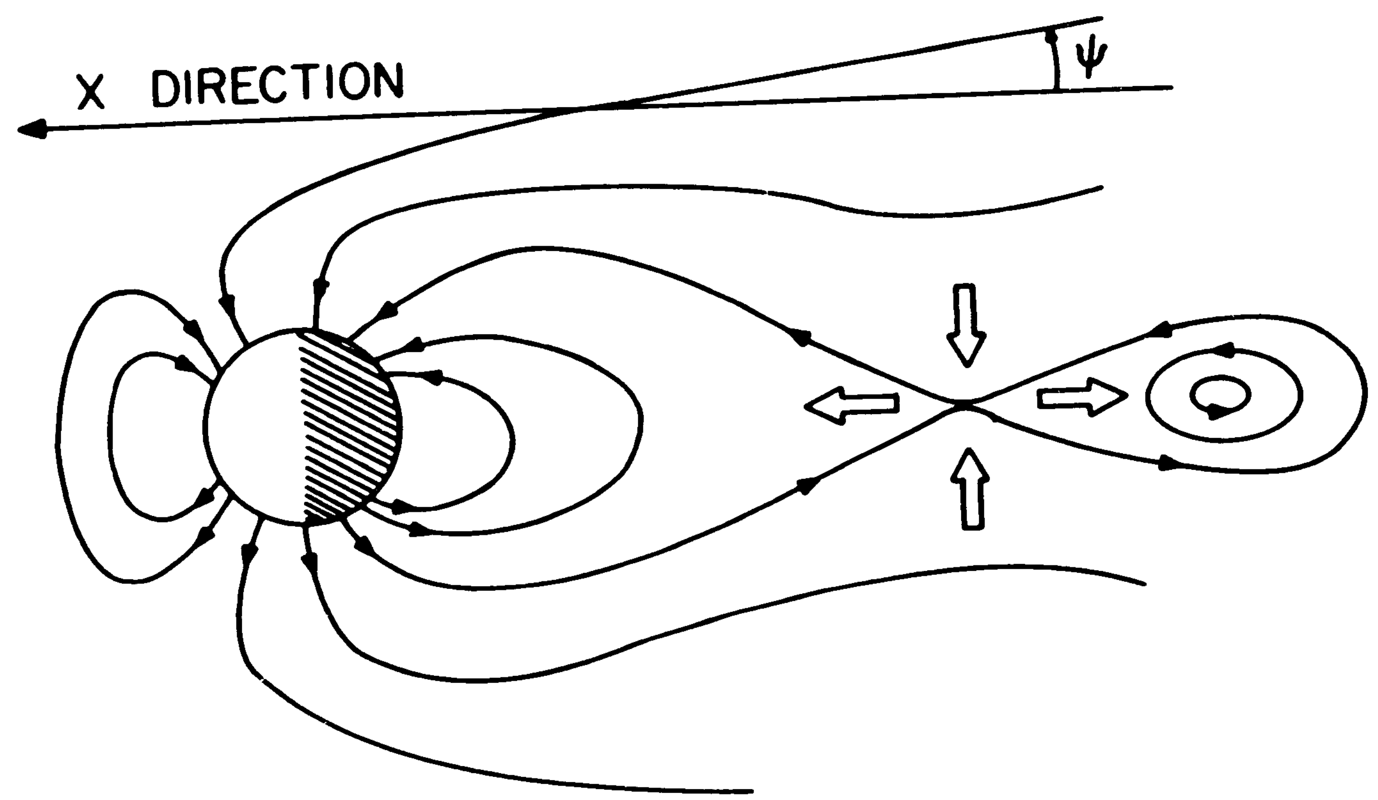

Figure 6